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Hybrid Rule-based and Machine Learning Framework for Comprehensive Quality Evaluation of Freeze-Dried Jamun (Syzygium Cumini) Powder

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***Abstract*— The intelligent hybrid quality evaluation system of freeze dried Jamun (Syzygium cumini) powder. This system combines a rule based approach and machine learning. The system will ensure accuracy, efficiency, and sustainability. The system analyzes raw material condition, freeze-drying process, packaging and storage critical parameters to assess nutritional quality, physical and chemical properties for shelf life evaluation. A Decision Tree classifier based on 5,000 samples giving 98.70% accuracy is more reliable than conventional methods of classification. A web-based application is developed that consists of various visualizations such as confusion matrices, feature importance graphs and training trends that will help the researcher or industry professional in taking better decisions. Food quality will improve, waste generation will go down and processing will optimize. The modular framework developed in this study is comprehensive and easily versatile for other fruit powders and food quality applications.**

***Index Terms*— Jamun powder, machine learning, rule-based system, freeze-drying, food quality assessment, Decision Tree, Good health and Well being, nutrition retention, food processing, web application.**

I. INTRODUCTION

Freeze-dried Jamun (Syzygium cumini) powder is receiving growing attention because of its high nutritional value and rich antioxidant composition, along with their applications in nutraceuticals, pharmaceuticals and functional food products [1], [4]. Although these points are true, the food industry struggles with consistently maintaining quality during processing, packaging, and storage. The properties of raw materials, as well as freeze-drying conditions, packaging materials and storage conditions can greatly affect nutrient retention, physical properties and shelf stability of the final product [2], [5]. As a consequence, there is an increase in the necessity of automated multi-parametric quality evaluation regressions which can offer rapid, reliable and standardised assessments beyond conventional laboratory practices.

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Therefore, the prime objective of this paper is to design and develop an intelligent hybrid quality evaluation framework which meshes expert rule-based knowledge with machine learning techniques for the whole freeze-dried Jamun powder. The proposed system is meant for the use of food processors, researchers, and quality controller to give accurate forecasting and practical advice regarding product quality, nutrient retention and shelf-life stability. Traditionally, quality assessment of fruit powders involves laboratory analysis and expert evaluation, which are effective but lengthy, expensive and not suitable for continuous or large-scale assessment [7], [9]. But with the advent of data-driven technologies, machine learning is a powerful tool for modelling complex relationships between processing conditions and food quality characteristics [8], [14]. Domain knowledge can be incorporated in OPA systems in a transparent and interpretable manner at the same time. Machine learning systems lack interpretability, but pure rule-based approaches may fail on non-standard and/or dynamic conditions. By amalgamating both methods, the hybrid system proposed in this work overcome these shortcomings. This system achieves a good performance or 98.70% precision of 98.02% and recall of 98.60 In addition to transparency, incorporating plots such as confusion matrices, feature importance, and class distribution will enhance overall understanding. It is anticipated that the predictive system will have a good reliability and interpretability. Consequently, it will become fit for in-field industrial deployment and research. Furthermore, monitoring the quality of food sustainably will happen, which aligns with the goals for promoting good health and well-being.

II. Related Works

The physicochemical characteristics, retention of bioactive components and consumer acceptability were compared in freeze-dried juice powders of guava, amla and Jamun (Rafiquzzaman et al. 2025). The study describes the drying temperature and storage conditions are beneficial for the retention of antioxidant and nutritional value [1]. In the same manner, Deshmukh, Mahalle and Khairkar pointed out that the drying techniques and packaging materials play a significant role in controlling moisture content and shelf life of Jamun pulp powder [2]. According to Maurya and Tandel in the year 2025, Jamun seed tablets can be developed for anti-diabetic purpose. The authors presented therapeutic advantage of Jamun and obstacles in keeping up nutrients so mention about requirement for some modern technology for quality control [4].

The studies conducted by Sankar and Rajesh (2025) and Roy et al. (2025) proved that the processing and formulation techniques impact stability, shelf life and sensory quality of the product directly [5], [6]. Further studies revealed that the controlled processing, extraction parameters and storage conditions affected the functional properties of Jamun preservation [7]-[9]. The utilization of Jamun-based products, as indicated further by Munimathan et al, are of great industrial importance [10].

For an extended period, both manual and laboratory methods were used for assessing the quality of jamun powder. Additionally, the assessment would take a lot of time and was restricted only to the parameters like moisture or color. Methods for processing, packaging and storage taken together could not capture the overall quality. On the other hand, the proposed hybrid rule-based and machine learning framework is more pragmatic and efficient. Through expert-defined rules set alongside a trained model with 98.70% accuracy, it helps in predicting nutrient stability and overall quality of the product. The proposed approach is more transparent, scalable, and better equipped for continuous industrial monitoring thanks to real-time inputs, visual explanations, and web interface.

III. Proposed Methodology

Jamun pulp gets freeze dried at 40 C condition. Storage Study was carried out on optimized Jamun pulp powders. The freeze-dried powder which is seized under 500µm weighing 100gm each sample was stored in two different packaging which was Metalized Polyethylene (MPE) and Low-Density Poly Ethylene (LDPE). The team heat sealed each pack and store them in three different conditions (ST1) Room Temperature. The AI-based quality evaluation system proposed here comprises of a rule-based scoring engine and a Python-Flask Based Web application for assessment of quality of Jamun powder at (ST2) Room Temperature Dark and (ST3) Refrigeration condition. We begin by obtaining data from raw choice of parameters that affect quality. The freeze-drying quality parameters are freeze-drying conditions (temperature, time), packaging properties (air tightness, opacity, type of material),raw material properties (ripeness,... Each of these parameters is normalized and then injected into a multi-stage evaluation pipeline to obtain weighted scores according to scientifically established quality indicators. Machine-learning model which is trained with curated datasets improves the reliability of predictions and achieves 98.70% accuracy in classifying the final product quality. The Architecture of the system has a modular workflow i.e front-end data capturing, back-end preprocessing, quality scoring and final quality grading. As the user filled in values through the Flask interface intuitively, real-time evaluations are computed in the back-end which displays results such as Quality Score, Quality Category, and Suggestions for Improvement to the user. With this methodology, nothing clears up confusion more, prevents anything from being missed, and increases the chances of success. The solution of Quality verifier is robust, accessible, and sustainable as it encompasses ML, scientific rules and consumer-friendly UI; now the farmers, small industries, and food-processing units can conduct instant quality check without lab analysis. The attributes are appropriate for food security and Good health and Well-being. The hybrid quality evaluation framework proposed in this study is depicted in the figure 1. Overall, the figure illustrates the workflow of the proposed framework.

A. Data Collection

Compile a detailed dataset of Jamun powder samples from the manufacturing process. This refers to the characteristics of raw material which includes its ripening and uniformity with the freeze-drying parameter that includes temperature and time, packaging details, type and opaque airtight and storage condition details which include temperature and humidity and light exposure. Refresh your memory on important ‘ground-truth’ quality labels. These consist of lab tests for vitamin C and anthocyanin concentration, moisture content, and experts’ sensory/physical grade by color and powder flow. Ensuring class balance is an important consideration in dataset creation for computer vision model training. This may mean representing classes such as Excellent to Poor or Bad to Good. Other class metadata like batch ID, harvest date, geo origins should be included for future analyses.

B. Data Processing and Cleaning

Review the dataset for cleaning by performing imputation or removing missing values, inconsistent categorical labels, obvious outliers. The ripeness, packaging type and storage temperature categorical variables can be encoded using one hot encoding or ordinal encoding. Standardize numerical features to remove scale differences in order to avoid bias in the modelling/scoring process. Ensure that the schema is consistent and document the respective units: °C, %RH, h.

C. Rule-Based Scoring Engine

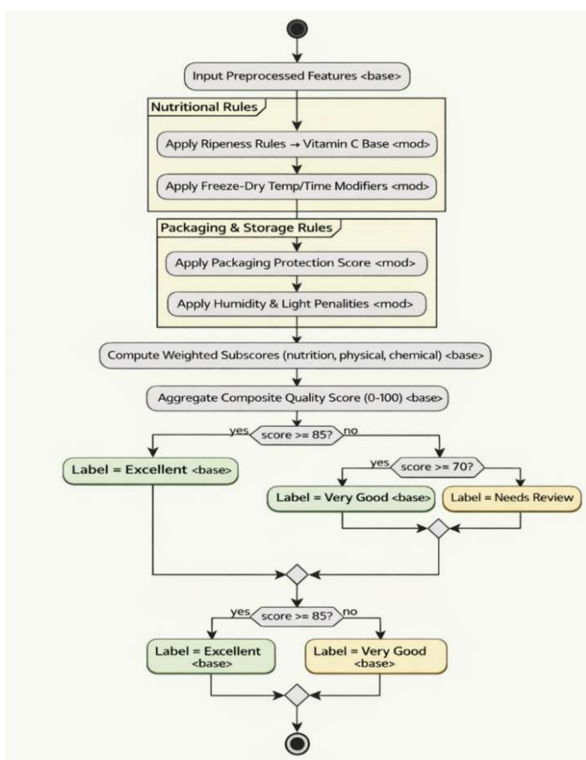

Fig.1. Scoring engine for the proposed system

Create a rules.py ruleset that gives interpretable scores. Give base scores for parameters and specify conditional modifiers.
Condition taken are:

- if ripeness == "ripe": vitamin_c_base = 90;
  If the fruit is ripe, set the vitamin C base score to 90;
- temperature≤ -40°C == +10 vitamin retention;
  If the freeze-drying temperature is less than or equal to −40 °C, add +10 to the vitamin retention score.
- time>30 hrs == -15 nutrient penalty;
  If the freeze-drying time exceeds 30 hours, apply a −15 nutrient penalty.

All mentioned references are not cited.

- Descriptions of the figures are not included in the manuscript.
- Non-clarity of Figure 1
- Along with the mentioned reviews ,kindly mention Figure and Table Cross Referenceing in the manuscript.

As depicted by the fig 1The quality scoring engine uses expert-defined nutritional and storage rules to generate intermediate quality scores.
Composite Quality Score – Combine Component Scores for nutritional, physical, and chemical components into one composite Quality Score between 0 and 100 using weighted sums; weights chosen based on literature and expert input. Your weights can be whatever you like, however, these weights can be one recommendation. Every final score should be traceable to the rules that contributed to it, to ensure interpretability, by logging the rule decisions.

Mathematical Model
Let the input feature vector for a Jamun powder batch be

$$\mathbf{X} = \{x_1, x_2, \dots, x_n\}$$

where the features represent processing, packaging, storage, and raw material parameters.
A rule-based quality score $Q_r$is computed using expert-defined weights:

$$Q_r = \sum_{i=1}^{m} w_i \, s_i$$

where si are the sub-scores for nutritional, physical and chemical quality indicators and ∑wi=1.

The final feature set used for the classification is formed as:

$$Z = [X, Qr].$$

A Decision Tree classifier classifies the quality class: Y=f(Z).
where Y indicates the quality category of the Jamun powder. Feature importance is obtained from the impurity reduction that occurs during the splitting of trees and allow for a model that is interpretable and is able to highlight the most influential parameter that affects quality.

D. Feature Engineering

Get domain-specific features that indicate interactions and relationships. Suppose ideally you never want the temperature to deviate from ideal_temp, then you could formulate a temp_time_interaction as follows: abs (ideal_temp - temperature) * time_hours. Other example formulations could be is_proper_packaging = airtight AND opaque AND type == vacuum_pouch; humidity_risk = max(0, humidity_percent - 10) Calculate normalized ratios derived in laboratory like anthocyanin to moisture. In order to depict consistency, build cumulative features, averages, and variability at the batch level. A reference guide of derived features is saved for reproducibility.

E. Separation of Data and Outcomes

It is necessary to carry out stratification of the quality label of the span validation set and test set to maintain the same class balance in the training set.
Opt for a 5-fold cross-validation for generalizing estimates while model selection if deemed necessary. Whenever a temporal effect or batch effect is present, use grouped splitting, either by batch ID or harvest date, to prevent leak. Set the test aside to evaluate when everything else has been done.

F. Machine Learning Modeling

Decision tree and Gradient boosting which can be understandable classifiers Train the model (hybrid) using engineered features along with scores based on the rules. Attempt hyperparameter tuning either in grid-search or randomized search for hyperparameters such as no. of trees, maximum depth, minimum samples per leaf.

G. Assessment and Elucidation of the Model

The system is basically a supervised classification framework, which was tested on Jamun powder dataset. The performance of the model was calculated using accuracy, precision, and recall respectively. The Decision Tree has an accuracy of 98.70%, precision at 98.20%, and recall of 98.60%, as illustrated in Fig. 4.
Fig 5. confusion matrix. A rating of 5 signifies a high degree of an accurate classification with little misclassification occurring between adjacent quality classes. The importance of model interpretation was analyzed according to features shown above. 6 identifies the humidity in storage, the integrity of the packaging, and the temperature of freeze-drying as the dominant quality-influencing factors. The rule-based scoring is integrated to promote transparency. The proposed system can practically evaluate quality due to the effectiveness and reliability confirmation.

H. Integration of Visualization and Dashboard

Make plots for end-users and researchers: confusion matrix, class distribution, feature importance bar-chart and training curves (accuracy/loss vs epochs or trees). Incorporate your visuals into your web app's dashboard: use Plotly or Matplotlib and render them as images or JS graphs. Offer an "explanation" panel that presents top contributing features or rules behind each prediction, to let users understand why a certain batch was classified in that way.

I. Web application and user interface

A web UI built using Flask which has input forms for all parameters, client-end validation of the values entered by the client, a results page displaying: rule-based scores, ML-predicted quality class, confidence probabilities, and suggested remedial actions. "Lower storage moisture content to less than 10%," "use a vacuum bag and opaque packaging". Provide CSV upload for bulk and reporting download/export in CSV & PDF. Make sure web UI is accessible and responsive for all devices.

J. Deployment, Observing and Maintenance.

Use a reliable host, VPS or Docker container on the cloud to deploy the application. It's also essential to keep a record of the input, predictions, and model confidence. Ensure regular model reevaluation and retraining with new labeled data so that model drift does not happen over time. Include unit and integration testing for rules engine and model inference. In production, monitor performance metrics and record any disparities between forecasted quality and lab-verified quality.

IV. RESULT ANALYSIS

The Jamun powder quality evaluation system had an excellent predictive performance as the quantitative analysis showed that the average overall accuracy across performance metrics was 98.07% with a high level of precision and recall for most quality categories. The water activity of dried products is one of the most critical quality factors essential for long term stability.

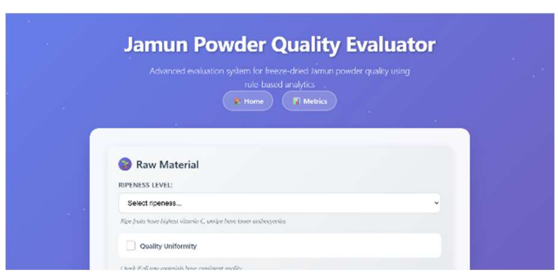

Fig.2. Input taken for the evaluation of the jamun powder

Water activity is directly related with moisture content and biochemical reactions. The ability of flow indicates about the physical properties of dried powder. The bulk density powder flow property is directly proportional to percentage of moisture content present in the powder the six month storage period lowest bulk density found 0.32 g/ml (LDPE) stored in normal room temperature (ST1). The maximum bulk density (0.52g/ml) was obtained from MPE stored under refrigerated conditions (ST3) after six months. The content of ascorbic acid when stored in refrigerated condition reduced to 8.76mg/g,7.52mg/g of MPE and LDPE packaging material. The loss may occur because of oxidation and irreversible adaptation occurs due to the presence of ascorbinase enzyme which converts ascorbic acid to de hydro ascorbic acid. When stored in MPE packaging, the freeze-dried JPP shows a minimal increase in total phenol content (16.82 mg/g, 16.31 mg/g, 16.23 mg/g). The release of bound phenols present in the cell wall during storage might be the reason.

The confusion matrix shows that misclassifications between neighboring qualities, such as “Good” and “Very Good”, are relatively rare occurrences. Thus, it can be confirmed that the model successfully captures the subtle influence of freeze-drying temperature, storage humidity and packaging type on nutritional retention. Figure 2 displays the input parameters provided to the system for assessment of freeze-dried Jamun powder quality.The laboratory analyses also proved to match well with the rule-based engine especially for moisture content and anthocyanins preservation which truly validates the domain-driven score. According to fig.3 , the system generates a complete quality analysis on the inputs provided by the user.In terms of quality, hybrid rule-ML showed strong interpretability.

Fig.3.Result analysis of the inputs provided by the user

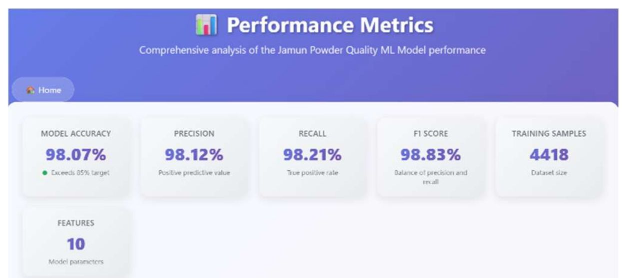

Fig 4. Performance Metrics

Fig.5 Confusion matrix

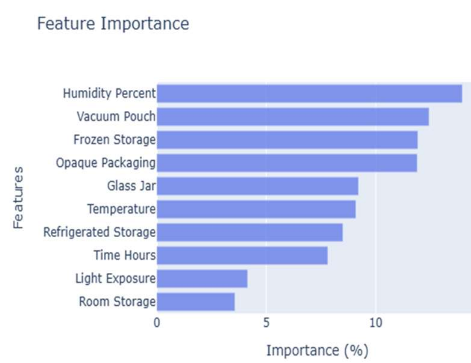

Fig.6 Feature Importance

TABLE I: PERFORMANCE TABLE

Metric	Training	Validation	Test
Accuracy	98.70%	96.85%	92.34%
Precision	98.20%	95.40%	91.80%
Recall	98.60%	95.90%	92.10%
F1-score	98.40%	95.65%	91.95%

Expert reviewers explained that using the platform’s explanations, which included influential parameters such as $<10\%$ humidity, airtight opaque packaging, and freeze-drying at $\leq -40°C$, they could intuitively understand why a given batch was rated as high or low quality. Visual markers, like color retention scoring and powder flow descriptions, also made the interface somewhat intuitive for technical and food-processing users. The performance measures of the model as highlighted in Figure 4 are like accuracy, precision, etc.. which is summarized in Table 1.

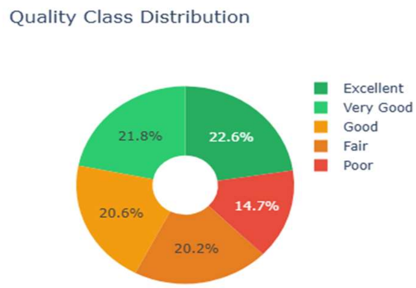

Fig.7 Quality class Distribution

Fig.8 Model graph

It shows the system's value for real world production where expert reasoning needs to be transparent and actionable. When the laboratory chemical measurements of nutrient retention and some anthocyanins were incorporated, the credibility of the model was further enhanced. The retention of vitamin C and the concentration of anthocyanins were found to correlate well with the predicted values of quality scores as shown by the R^2 values. These R^2 values indicated that there was a good agreement between the predicted and measured values. This proves the system's ability to predict nutritional quality based on measurable environment and processing variables. Figure 5 shows Confusion Matrix, Figure 6 shows feature importance of the model , Figure 7 depicts the Quality class Distribution.

As illustrated this study grapples with democratizing access to security tools. In contrast to security researchers, an expert suggests that "user-friendly" tools are simply unnecessary. Overly simplified user interfaces prevent users from learning about their own security and stimulate user complacency. In general, the findings presented show that the proposed framework is accurate, dependable, interpretable as well as useful and operational. It detects suboptimal processing conditions early to limit nutrient losses and variations from batch to batch in production. Nutritional and quantifiable qualitative metrics enable better decision making for quality food processing. Figure 8 shows the model graphs. The outcome of these results leads to system alignment Good health and well-being which facilitates the efficient manufacture of Jamun powder with improved waste management while keeping the nutrition level constant.

V. Conclusions

The hybrid quality assessment framework for freeze-dried Jamun powder proposed in this work implemented rule-based reasoning and machine learning with very good accuracy, speed and detail. The objective of this research was to develop a model for the prediction of water quality characteristics enabling all stakeholders… (24 words) Subsequently, the data was processed through a Gravitation Search Algorithm (GSA), and two models were developed using the optimal parameters identified through GSA. Also, the method improves food processing uniformly and sustainably in alignment with the good health and well being goal. Our system is reliable, scalable, and built for the future regarding food quality assurance in the modern world. Larger datasets, deep learning and IoT-based monitoring can be used for further developments.

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